Magnetic cluster phases of Mn-interstitial-free (Ga,Mn)As

Y. J. Cho,[1] M. A. Scarpulla,[2] X. Liu,[1] Y. Y. Zhou,[1]
O. D. Dubon,[2] and J. K. Furdyna[1]

[1]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[2]*Department of Materials Science and Engineering, University of California, Berkeley, California 94720, USA*

Abstract. We report an investigation of magnetic cluster phases of (Ga,Mn)As of varying dosages formed by Mn ion implantation followed by pulsed-laser melting (II-PLM). A systematic study of zero-field-cooled and field-cooled magnetization along several high-symmetry crystallographic directions reveals the presence of magnetic cluster-like phases, and manifests an unambiguous in-plane uniaxial anisotropy in all samples. Since such anisotropy has been previously seen in (Ga,Mn)As grown by molecular beam epitaxy, its observation in (Ga,Mn)As prepared by II-PLM suggests that it is an intrinsic property of (Ga,Mn)As rather than a consequence of a specific growth method. Our results also indicate a unique uniaxial component along $[\bar{1}10]$ for the magnetic cluster phase at intermediate Mn dosage indicating that composition as well as processing may determine the details of the magnetic anisotropy in (Ga,Mn)As.

Keywords: ferromagnetic semiconductors; magnetic anisotropy; implantation; pulsed-laser melting; magnetic phases.
PACS: 75.50.Pp, 75.50.Dd , 75.30.Gw, 75.70.Ak, 68.55.Ln, 61.72.Vv, 75.60.Ej, 75.30.Kz

Although extensive efforts have been made to understand the magnetic anisotropy of (Ga,Mn)As, principally based on models involving hole-mediated ferromagnetism,[1,2] the mechanism of in-plane uniaxial anisotropy observed in (Ga,Mn)As grown by low temperature molecular beam epitaxy (MBE) remains unclear. Hamaya *et al.* have recently suggested that the in-plane uniaxial anisotropy may originate from spin-glass-like cluster phases existing within the cubic (Ga,Mn)As matrix.[3,4] Herein, this issue is explored using zero-field-cooled (ZFC) and field-cooled (FC) magnetization (M_{ZFC} and M_{FC}) along several high-symmetry crystallographic directions on a series of Mn-interstitial-free (Ga,Mn)As specimens prepared by Mn ion implantation and subsequent pulsed laser melting (II-PLM).[5,6]

Semi-insulating GaAs (001) wafers were implanted with 80 keV Mn ions to one dose of 5×10^{15} cm^{-2} Mn ions (Sample #1); two doses (Sample #2); and four doses (Sample #3). The implanted samples were irradiated in air with a single pulse from a KrF excimer laser (248 nm, ~30 ns), causing the implanted layer to first melt and then re-crystallize upon solidification. This process leads to high levels of Mn incorporation in the re-crystallized (Ga,Mn)As layer, while suppressing the formation of Mn interstitials.[7] The Curie temperatures (T_Cs) are near 30 K, 60 K, and 80 K for Samples #1, #2, and #3, respectively. Using ferromagnetic resonance and magnetization hysteresis loop measurements, all three samples show the unambiguous presence of an in-plane uniaxial anisotropy similar to that observed in MBE-grown (Ga,Mn)As film.[8] Since the samples were produced by an entirely different process, this result supports the hypothesis that the breaking of in-plane cubic symmetry is an intrinsic property of (Ga,Mn)As films.

Figure 1 shows the temperature dependences of M_{ZFC} and M_{FC} for Samples #1 (a), #2 (b), and #3 (c). M_{ZFC} was obtained by first cooling the sample in zero magnetic field from $T > T_C$ to 4 K. A dc magnetic field of 35 Oe was then applied along [110], $[\bar{1}10]$, [001], or in-plane <100> directions, and the magnetization was measured as the temperature was increased. M_{FC} was obtained in a similar way, except that the sample was cooled in 35 Oe. Except for the results on Sample #2 along $[\bar{1}10]$, there are clear differences between M_{ZFC} and M_{FC} in all cases. Such dependence on thermal history is usually attributed to the existence of spin glass and/or magnetic cluster phases.

The ferromagnetic ordering in the lowest-dosed sample (#1) is believed to be local based on its rapidly increasing resistivity with decreasing temperature. We thus expect phenomena associated with magnetic clusters to dominate the magnetization for all directions. Interestingly, for this sample the easy

CP893, *Physics of Semiconductors, 28th International Conference*
edited by W. Jantsch and F. Schäffler

magnetization axis is the perpendicular [001], rather than the in-plane <100> found for the other samples.

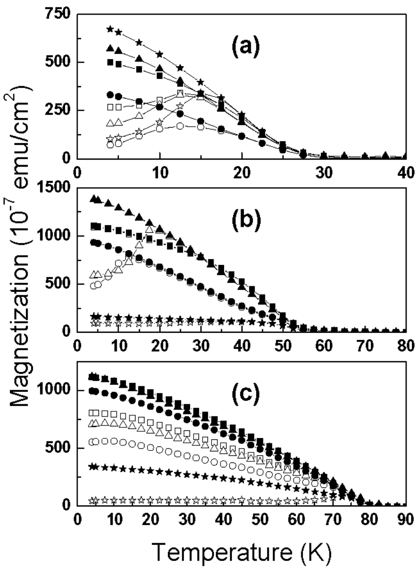

FIGURE 1. M_{ZFC} and M_{FC} as a function of temperature for Samples #1 (a), #2 (b), and #3 (c). An external magnetic field of 35 Oe is applied parallel to either [110] (circles), $[\bar{1}10]$ (squares), [001] (stars), or to the in-plane <100> directions (triangles). M_{ZFC} data are denoted by open symbols; M_{FC} by full symbols.

As for Sample #2, magnetic cluster-like behavior along $[\bar{1}10]$ is ruled out because there is no difference between M_{ZFC} and M_{FC} along that direction. Temperature dependence of magnetization induced by a minute residual field (~1.5 ± 1.0 Oe) in Sample #2 is plotted in Fig. 2. Note that such minute field exists also during the process of ZFC. For this sample, temperature dependent M_{ZFC} and M_{FC} obtained for **H**(35 Oe)$\|[\bar{1}10]$ is also plotted in Fig. 2. The three conditions along $[\bar{1}10]$ give almost identical results. Importantly (and in contrast with Fig. 1(b)) the magnetization along $[\bar{1}10]$ for Sample #2 is the highest for the vanishingly small cooling field. By applying a stronger cooling field (~35 Oe), however, we obtain the largest magnetization in the <100>.

For Sample #3, magnetic cluster-like behavior is again dominant along all directions, similar to Sample #1. Although twice the Mn dosage of Sample #2 was implanted in Sample #3, the values of its magnetization at low temperature are lower than those observed in Sample #2, as shown in Fig. 1. Therefore, we postulate that the fraction of non-substitutional of Mn ions (possibly in the form of Mn clusters or MnAs precipitates (but not as interstitials in tetrahedral or hexagonal sites) increases with increasing Mn dosage. These Mn complexes may obstruct ferromagnetic interaction among substitutional Mn ions, thus decreasing the magnetization and enhancing the cluster-like magnetic behavior in this specimen.

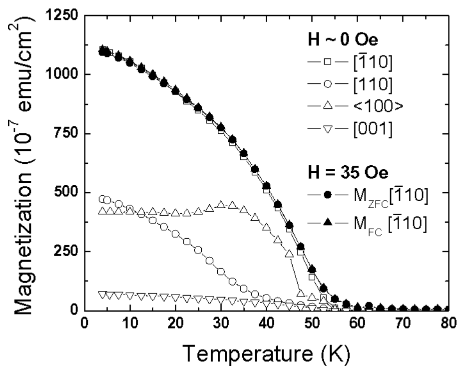

FIGURE 2. Temperature dependence of magnetization induced by a small residual field (~1.5 ± 1.0 Oe) in Sample #2 along either [110], $[\bar{1}10]$, [001], or in-plane <100> axes. For comparison, temperature dependences of M_{ZFC} and M_{FC} obtained at **H**(35 Oe)$\|[\bar{1}10]$ for Sample #2 are also plotted. Note the striking fact that the three conditions give almost identical result for $[\bar{1}10]$.

To sum up, direct magnetization was used to study magnetic cluster behavior in II-PLM (Ga,Mn)As. Based on obvious differences between the observed M_{ZFC} and M_{FC}, we conclude that magnetic cluster-like phases exist in all samples studied in this series. It is also observed that every specimen in the series has a $[\bar{1}10]$ uniaxial anisotropy; and that both M_{ZFC} and M_{FC} measured along that direction are highly sensitive to the Mn dosage. It is interesting that the magnetic cluster anisotropy in Sample #2 (with an intermediate Mn implantation dosage) is different from that in Samples #1 and #3. The present results suggest that further investigation of the cluster-like phases in III-Mn-V alloys should shed important light on the magnetism in these materials.

Supported by NSF Grant DMR06-03752 and NSF-NIRT Program DMR02-10519 and by the U.S. Department of Energy under Contract No. DEAC02-05CH11231.

REFERENCES

[1] T. Dietl, J. Phys.: Condens. Matter **16**, S5471 (2004).
[2] X. Liu and J. K. Furdyna, J. Phys.: Condens. Matter **18**, R245 (2006).
[3] K. Hamaya *et al.*, Phys. Rev. Lett. **94**, 147203 (2005).
[4] K. Hamaya *et al.*, Phys. Rev. B **73**, 155204 (2006).
[5] M. A. Scarpulla *et al.*, Appl. Phys. Lett. **82**, 1251 (2003).
[6] M. A. Scarpulla *et al.*, AIP Conf. Proc. **772**, 1367 (2005).
[7] M. A. Scarpulla *et al.*, Phys. Rev. Lett.**95** 207204 (2005).
[8] Y. J. Cho *et al.*, (unpublished).